Dark matter from Affleck-Dine baryogenesis

Alexander Kusenko

Department of Physics and Astronomy, University of California, Los Angeles, CA 90095-1547

Abstract. Fragmentation of the Affleck-Dine condensate into Q-balls could fill the Universe with dark matter either in the form of stable baryonic balls, or LSP produced from the decay of unstable Q-balls. The dark matter and the ordinary matter in the Universe may share the same origin.

The Affleck-Dine (AD) scenario for baryogenesis [1] has several appealing features. First, the requisite scalar degrees of freedom with a non-zero baryon number are necessarily present in theories with low-energy supersymmetry. Second, the scalar potential of the MSSM and other supersymmetric generalizations of the Standard Model has numerous flat directions. At the end of inflation, the scalar fields develop large expectation values along these flat directions setting the stage for the AD scenario. The most economical supersymmetric extension of the Standard Model, MSSM, with some appropriate supersymmetry breaking [2], is already sufficient for the AD baryogenesis [3]. Finally, the observed value of the baryon asymmetry, $\eta_{_B} \sim 10^{-10}$, can easily be accommodated in this scenario.

Supersymmetry also predicts the existence of non-topological solitons, Q-balls [4], with non-zero baryon and lepton numbers [5]. The interior of these Q-balls has the same field structure [6] as the AD condensate; and, in fact, very large Q-balls can form via the fragmentation of the scalar condensate in the early Universe [7,8].

Depending on their size and the mode of supersymmetry breaking, the baryonic balls formed in the process of AD baryogenesis can be stable or unstable. If they are stable, they can presently exist as a form of dark matter [7] with distinctive observational signatures [9]. If they are unstable [10], the LSP produced from their decay can contribute to dark matter [8]. In both cases, the ordinary matter and the dark matter come from the same origin, the primordial scalar condensate, and the amounts of dark matter ($\Omega_{_{DM}}$) and the ordinary matter ($\Omega_{_M}$) are related [11,12]. One may hope to understand, therefore, why $\Omega_{_M}$ and $\Omega_{_{DM}}$ are the same order of magnitude. This equality is inevitably fortuitous in theories that assume the dark matter formed as a result of a freeze-out or other process unrelated to baryogenesis (see, however, Ref. [13]). If, however, both components arise from AD baryogenesis, it is reasonable to ask whether a relation $\Omega_{_M} \sim \Omega_{_{DM}}$ can have a natural

explanation [11,12].

At the end of inflation, the scalar fields acquire large expectation values along the flat directions and begin to roll towards their potential minima. Under very generic conditions, such a motion of the scalar condensate can become unstable with respect to small coordinate-dependent perturbations [7]. For an adiabatically slow motion of the initially homogeneous condensate $\phi(x,t) = \rho(t)\exp(i\Omega(t))$, the instability sets in when the second derivative of the potential, $U''(\phi(x,t)) \equiv U''(\rho(t))$, is smaller than $(d\Omega(t)/dt)^2$. We note in passing that for many potentials, in particular, those that arise as a result of gauge-mediated supersymmetry breaking, $U''(\phi(x,t))$ can be negative for some values of ϕ, in which case the condition $U''(\phi(x,t)) < (d\Omega(t)/dt)^2$ is satisfied automatically. If the expansion of the universe occurs at a rate that allows this instability to grow, the condensate becomes inhomogeneous and breaks up into Q-balls.

Q-balls produced from the shattered AD condensate can further evolve by absorbing baryons from or releasing baryons into the surrounding plasma [12,14].

Stable baryonic Q-balls can be the dark matter. Their signatures [9] in different detectors are characterized by a straight track with a large energy deposition, $\sim$ 100 GeV/cm, and no attenuation throughout the detector volume. The dark-matter Q-balls would have typical galactic velocities $\sim 10^{-3}c$. Assuming an order-one contribution to energy density of the Universe, one can set limits on their flux and, hence, their baryon number Q_B. The present limits require that $Q_B > 10^{22}$ [9,15]. The predicted range for Q_B consistent with $\Omega_M \sim \Omega_{DM}$ is $Q_B = 10^{26\pm2}$ [12].

The entire cosmologically interesting range of dark-matter Q-balls [7,9,12] can be explored by a detector with a surface area of several square kilometers. Since the required sensitivity is extremely low (thanks to the huge energy release expected from the passage of a superball), it is conceivable that a relatively inexpensive dedicated experiment could perform an exhaustive search and ultimately discover or rule out the stable Q-balls as dark-matter particles.

Baryonic Q-balls can absorb protons and neutrons, a process accompanied by a release of energy. This is because a stable baryonic ball has a smaller mass than a collection of neutrons with the same total baryon number. As a result, primordial Q-balls can accumulate in the center of a neutron star, grow through an absorption of neutrons, and eventually reduce the neutron star mass below the limit of its stability, which is about $0.2M_\odot$. At that point gravity is no longer strong enough to keep the neutrons from decaying, and the star explodes [16]. The lifetime of a neutron star is of order $(m/200\mathrm{GeV})^5$ Gyr, where m is the scale associated with supersymmetry breaking. Perhaps, these mini-supernova explosions [17], which release of order 10^{52} erg, can be observable; they may also be related to (some) gamma-ray bursts.

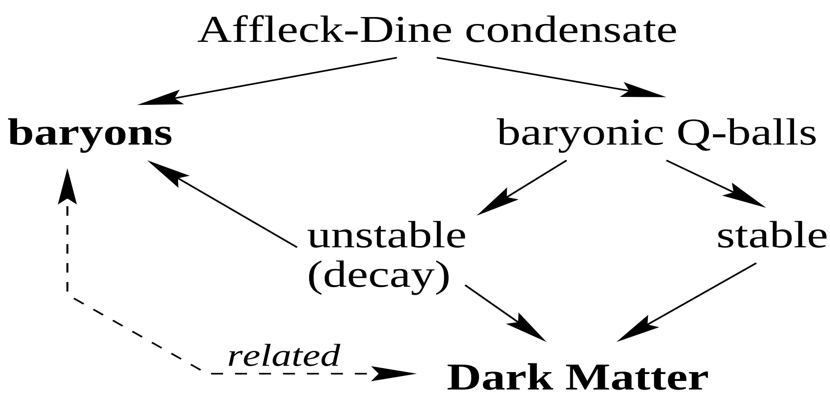
The cosmological limits on dark mater impose some constraints on the form of the potential along a flat direction responsible for baryogenesis [18]. Thanks to the sensitivity of the Q-ball properties to the high-energy scales (*cf.* [19]), one may hope to learn about the higher-dimensional operators due to the Planck-scale physics, as well as the supersymmetry-breaking terms that lift the flat directions [18].

Enqvist and McDonald have suggested that the unstable SUSY Q-balls can also play a role in the production of dark matter [8,11,20–22]. The decay of a SUSY Q-ball into quarks is accompanied by the production of the lightest supersymmetric particles [8] that contribute to dark matter. This scenario offers an explanation of why $\Omega_{_M} \sim \Omega_{_{DM}}$ [11] because the dark-matter neutralinos are produced non-thermally with a number density that is related to the density of baryons. This scenario fits naturally in cosmology with a D-term inflation [23] and a reheating temperature below $10^{4\pm1}$ GeV [20].

Formation and decay of the unstable SUSY Q-balls could cause the isocurvature fluctuations that may be observable by MAP and PLANK [21].

The scenarios described above were studied in the context of MSSM. Of course, some additional scalar fields with global charges that often appear in the non-minimal SUSY models can also form stable Q-balls [24]. The non-abelian Q-balls [25], as well as the Q-balls associated with the conservation of a gauge charge [26], may also play an important role in cosmology.

To summarize, the Affleck-Dine baryogenesis in the MSSM can produce both the matter nucleons and the lumps of the scalar condensate, Q-balls. The stable Q-balls, as well as the products of the decay of the unstable Q-balls can contribute to dark matter. These possibilities are illustrated by the following diagram:



Formation of Q-balls can have profound implications for cosmology[1]. Since the fragmentation of a coherent scalar condensate [7,8] is the only conceivable mechanism that could lead to the formation of very large Q-balls, their observation would seem to speak unambiguously in favor of such process having taken place. Thus, although non-observation of Q-balls cannot rule out the AD baryogenesis, their observation would be a definite confirmation thereof. In addition, the decay of unstable SUSY Q-balls could produce the LSP dark matter at late times and out of equilibrium.

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[1] For a more detailed review, see, *e. g.*, Ref. [27].

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